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Versatile Nanodeposition of Dielectrics and Metals by Non-contact Direct-Write Technology

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ABSTRACT

Direct-write techniques allow processing in the nanometer range and have become powerful methods for rapid prototyping of microelectronic circuits and micro-electro-mechanical systems (MEMS). Chemical reactions are initiated by a focused beam leading to deposition of solid material on literally any surface. We have used this method to deposit metals such as tungsten and dielectrics such as silicon oxide using a focused ion beam (FIB) with 10 to 50 kV acceleration voltage. Controlled guidance of the beam allows deposition of both metallic and dielectric material with features in the 100 nm range. The deposition of separate structures of metallic and dielectric material deposited next to each other is shown on samples of different roughness. 3-dimensional exemplary prototypes in the sub-µm range and multilayer structures demonstrate the versatility of this method for prototyping and mix-and-match approaches with commercial semiconductor devices. A characterization of the deposited material was performed to clarify chemical composition and surface morphology of deposited structures. The deposition parameters were found to influence the chemical composition and electronic properties of the material. Direct-write deposition of dielectrics and metals by FIB allows fabrication of 3-dimensional prototypes with custom-tailored material properties.

INTRODUCTION

Direct-write techniques have become increasingly important for rapid prototyping of microelectronic circuits and MEMS as these direct-write methods allow access to the nanometer range [1,2]. These non-contact techniques typically use energetic focused beams to facilitate processing on a locally confined space down to nanometer range. The focused beam makes it possible to initiate chemical reactions leading to deposition of solid material on literally any surface. In this work a focused ion beam (FIB) is used to deposit metals such as tungsten or dielectrics such as silicon oxide enabling the generation of prototypes for microelectronic applications. With deliberate control of the beam position a point-by-point deposition of both metallic and dielectric material is achieved [3]. The smallest features obtained with this direct-write method were below 100 nm.

The advantage of the direct write technique is that it is a mask-less approach. Therefore, prototypes can be realized quickly and cost-effectively. Unlike optical projection lithography no photomask needs to be produced and changes of the layout can be implemented quickly. This provides the long sought flexibility to device development. Furthermore, the feasibility to fabricate spatial structures extends the application range towards creation of 3-dimensional devices. With beam-induced direct-write techniques the deposition of material is feasible regardless of the roughness or prior structure of the sample and the suitability of these methods for mix-and-match techniques is demonstrated in this work by direct-write deposition on commercial microchips.

With FIB-CVD individual structures of metallic and dielectric material may be deposited next to each other. Several exemplary prototypes such as functional MIM (metal-insulator-metal) capacitor structures and geometrical modifications of 3-dimensional substrates such as AFM (atomic force microscope) cantilevers demonstrate the feasibility of this method for the generation of functional multimaterial structures in the sub-μm range. The deposition parameters have a strong influence on the chemical composition and electronic properties of the material. Therefore, a chemical and physical characterization of the materials is performed. These material attributes will impact the final performance of both electronic and mechanical devices. Direct-write deposition allows for custom tailoring and fine-tuning of material properties. These direct-write techniques show a future potential for prototyping of 2- and 3-dimensional components [4, 5].

EXPERIMENTAL DETAILS

Direct-write deposition of layers and 3-dimensional structures of silicon oxide and tungsten was performed by chemical vapor deposition (CVD). The CVD process was locally induced by a focused ion beam (FIB). The silicon oxide deposition was obtained by decomposition and reaction of a binary precursor gas mixture of siloxane and oxygen while the metal deposition was achieved by local decomposition of tungstenhexacarbonyl precursor. The deposition chamber had a base pressure of 10E-7 Torr. Introduction of precursor gases increased the total pressure to the 10E-6 to 10E-5 Torr regime. Gaseous tetramethylcyclotetrasiloxane (TMCTS) and molecular oxygen were coadsorbed at the substrate surface. The surface reaction leading to deposition of dielectric material on the substrate surface was locally induced by an impinging Ga+ beam. Thus, the deposited material is confined to a restricted area from 0.01 μm^2 up to 1 mm^2. Direct-write techniques allow for arbitrary geometry relying only on the guidance of the focused beam. The ion beam could be focused down to a diameter of 5 nm. Smallest features deposited were in the 100 nm range due to overspray effects by sputtering and redeposition of previously deposited material.

The Ga ions were generated by a liquid metal ion source accelerated with 50 kV. An electrostatic lens system for focusing and a deflection system for scanning the beam provided a focused beam with an ion current adjustable between 4 pA and 2 nA. The pixel spacing during scanning could be adjusted in the nm to the μm range. For deposition the ion beam was directed perpendicular to the sample surface. Commercial Microchips or semiconductor materials such as Si (100) or GaAs were used as substrates.

Topology of the deposited structures was investigated by atomic force microscopy (AFM) using a Digital Instruments 3100 in tapping mode. The chemical composition of deposited materials was determined by secondary ion mass spectroscopy (SIMS) using a CAMECA IMS 3f sector field system. The SIMS-tool was operated in depth profiling mode to determine changes of chemical composition with varying layer thickness. A 15 nA Cs+ ion beam was focused on a 60 μm diameter spot of the 150x150 sample area. The recorded signal, as counts/min account for the concentration in the deposited material.

DISCUSSION

Direct-Write Deposition with a focused ion beam was evaluated for its appropriateness for practical applications. Therefore, the homogeny of the deposited material and the reproducibility of the process were examined. For numerous applications the morphology of the deposited material is essential so that the surface roughness of directly deposited material was investigated. To display the suitability for practical applications prototypes for multilayered and 3-dimensional structures were fabricated by FIB-Direct Write Deposition.

Chemical Composition

The chemical composition of silicon oxide deposited by FIB-CVD was investigated by secondary ion mass spectroscopy (SIMS). A depth profile of two individually deposited samples shows the composition of the material with the proceeding deposition (Fig. 1).

The SIMS-spectra prove a homogeneous chemical composition of the FIB-deposited material. This indicates a stable, robust process for the direct-write deposition of silicon oxide However, previous studies have shown that, at the substrate interface, an intermixing layer is formed under highly energetic ion bombardment [6]. During SIMS sputtering Si and O are the dominant species and also SiO ions are found signifying the existence of silicon oxide bonds. Furthermore, contaminations of C and Ga originating from the ion beam are observed. However, the logarithmic scale of the ion counts suggests silicon and oxide as the main components of the deposited material.

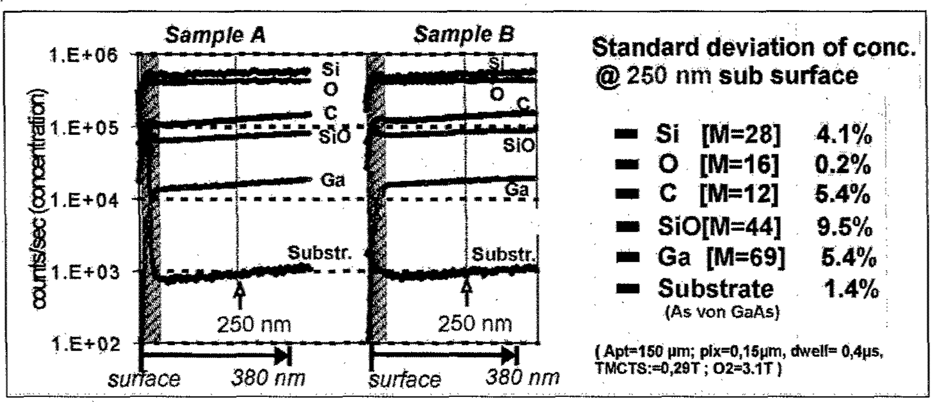

Figure 1. Chemical composition and reproducibility of silicon oxide deposition. Depth profiles of 2 silicon oxide structures fabricated separately but with identical process parameters were measured- the composition of the FIB-deposited material was analyzed by SIMS. The concentration variations of single species were calculated for the material composition at 250 nm sputter depth.

The comparison of the two individually processed samples renders the FIB-CVD direct-write deposition a highly reproducible process. The concentrations of all species are highly comparable between both samples. The ion counts of different species were compared for 250 nm sputter depth. The standard deviation of most detected species is below 5% and signifies an excellent repeatability. This allows employing direct-write deposition also for applications where a constant material quality is demanded. However, the variation of process parameters allows to change the chemical composition and to tailor material properties accordingly to meet specific requirements [7].

Surface Roughness

For mechanical applications the surface morphology is a central characteristic. The surface roughness of silicon oxide deposited by FIB-CVD was investigated by atomic force microscopy (Fig.2). The selection of the pixel spacing was found to have a significant influence on the surface roughness of the deposited material. All other process parameters such as total ion dose, dwell time per pixel and composition of the gas atmosphere were maintained invariable so that only the spacing between beam spot positions during a scan is responsible for the observed changes. With a small pixel spacing a very smooth surface with a RMS roughness in the 3 nm range was obtained (Fig. 2 left). With pixels positioned so close that neighboring beam profiles are overlapping a very a homogeneous deposition over the entire surface was obtained. Large pixel spacing resulted in a rough surface with a RMS roughness exceeding 10 nm. The large distance between neighboring beam spots led to a locally inhomogeneous ion exposure facilitating slightly different deposition rates in the sub-μm range.

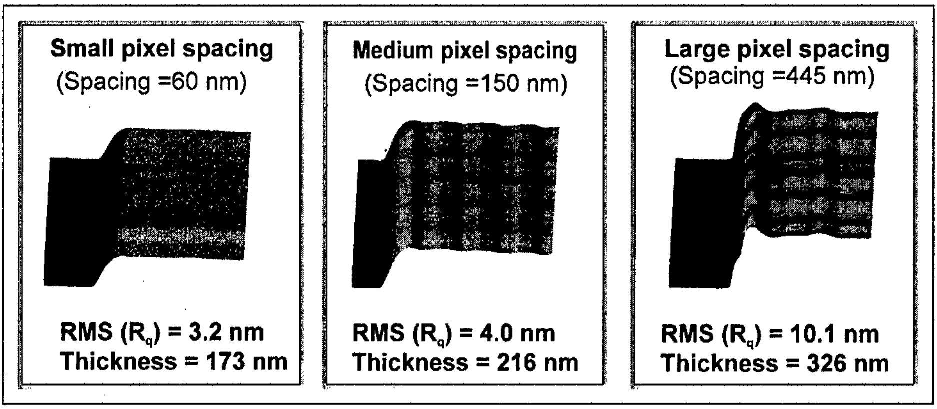

Figure 2. Surface roughness of FIB-deposited material. The morphology of silicon oxide fabricated by FIB-CVD was recorded by AFM. The process parameter pixel spacing - the distance between beam spots during the scan operation - was varied.

The different thickness of deposited material obtained with an identical ion dose in all cases has to be noted (Fig. 2). With ion induced deposition the resulting deposition rate is always in equilibrium between depositing new material by the FIB-induced CVD reaction and removing material again by ion sputtering. Large pixel spacing facilitates a more effective utilization of ions for deposition while the negative consequences of sputtering are diminished. By widening the pixel spacing the deposition rate could almost be doubled. This indicates a higher efficiency of the deposition process with large pixel spacing, but at the cost of a higher surface roughness. Chemical analysis by Auger electron spectroscopy showed lower Ga-concentrations with large pixel spacing, while the amount of Ga implanted in the deposited material was higher with a small pixel spacing.

3-dimensional Structures

Direct-write deposition is a versatile tool for fabrication of 3-dimensional structures. An experimental multilayer structure for interconnect modification of commercial microchips displays the capability to rewire an integrated circuit using three additional interconnect layers (Fig 3). With the multilayer interconnect metal lines were deposited by FIB-CVD to lay conductive paths. The metallic features are separated by silicon oxide, that was deposited by FIB direct-write deposition acting as interline and interlayer dielectric. Imaging by FIB allows aligning the structure to be deposited on the substrate surface. Positioning of individual metal interconnects can be performed in-situ during the fabrication process and without any necessity for a previously fabricated mask.

Direct-write deposition is also a powerful method for prototyping of 3-dimensional devices down to the sub-µm range. A structure with several pillars of 1x1 µm cross section was deposited (Fig. 4). An aspect ratio height to side length of 30 could be achieved with the shown structures. Also curved pillars were fabricated - a design that is not accessible with standard lithography techniques. This versatility in the design renders FIB direct-write deposition an excellent tool for development of new MEMS prototypes.

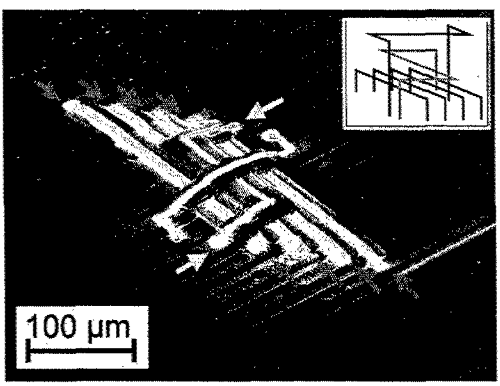

Figure 3. Multilevel interconnect prototype. On the surface of the commercial microchip a 3-layer interconnect structure was fabricated by FIB-CVD of tungsten (bright lines) and silicon oxide (thicker dark lines). The conductive metal lines are well separated by dielectric material.

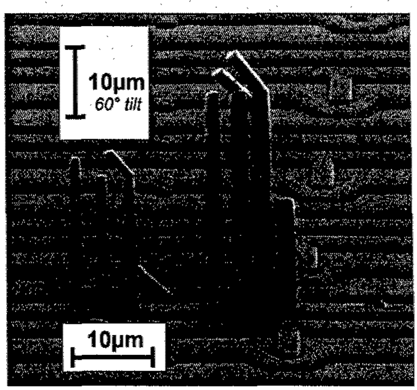

Figure 4. Two 3-dimensional structures fabricated by direct-write deposition of silicon oxide. The single pillars have a 1x1 µm cross section and are up to 30 µm high and are positioned on preselected spots.

CONCLUSIONS

We have shown that the direct-write deposition utilizing a focused ion beam is a versatile process that allows depositing metals and dielectric materials. The deposition process can be influenced in manifold ways by adjusting the process parameters in order to tailor the material properties such as chemical composition or surface roughness. The FIB-CVD process was shown to be highly reproducible and provides material of a homogeneous chemical composition. The capability to deposit conductive and insulating material renders direct-write deposition an ideal prototyping technique for microelectronics. The feasibility to directly deposit 3-dimensional structures of arbitrary shape down below 1μm feature size gives this method a high potential as development tool of future MEMS prototypes.

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